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Human Red Blood Cell Wright Antigens: A Genetic and Evolutionary Perspective on Glycophorin A-Band 3 Interaction

By Cheng-Han Huang, Marion E. Reid, Shen-Si Xie, and Olga O. Blumenfeld

The Wright (Wr^a/Wr^b) blood group polymorphism is defined by an allelic change (Lys658Glu) in the band 3 protein; nevertheless, the Wr^b antigen apparently requires glycophorin A (GPA) for surface presentation. To gain insight into the structural basis for this protein-protein interaction and delineate its relationship with Wr^b antigen expression, we investigated GPA and band 3 sequence polymorphisms occurring in rare humans and nonhuman primates. The lack of GPA or amino acid residues 59 through 71 of GPA results in the absence of Wr^b from human red blood cells (RBCs) exhibiting the M^kM^k, En(a−), or MiV phenotype. However, the SAT homozygous cells carried a Glu_{658} form of band 3 and a hybrid glycophorin with the entire GPA extramembrane domain from residues 1 through 71, yet expressed no Wr^b antigen. This finding suggests that formation of the Wr^b antigenic structure is dependent on protein folding and that the transmembrane junction of GPA is important in maintaining the required conformation. Comparative analyses of GPA and band 3 homologues led to the identification in the interacting regions of conserved and dispensable amino acid residues that correlated with the Wr^b positive or negative status on nonhuman primates. In particular, the chimpanzee RBCs cells expressed Wr^b and the Glu_{658} form of band 3, which is identical to humans, but their GPA contained the Gly rather than Arg residue at position 61. Taken together, the results suggest that (1) Arg_{61} of GPA and the proposed Arg_{61}-Glu_{658} charge pair are not crucial for Wr^b antigen exhibition and (2) the role of GPA for interaction with band 3, including Glu_{658}, probably involves a number of amino acid residues located in the α-helical region and transmembrane junction.

SINCE FIRST DESCRIBED,[1] the Wright (Wr) antigens in human red blood cells (RBCs) have attracted an intensive series of investigations.[2] There are two blood group antigens, the low-incidence Wr^a and the high-incidence Wr^b, that are considered to be antithetical and are produced as allelic forms of the same structural gene.[3,4] Despite the fact that alloimmunization may cause transfusion reactions and hemolytic disease of the newborn,[5] the functional significance of Wr antigens, if any, remains unknown. Furthermore, these antigens appear to be dispensable because no morphologic or functional abnormalities are manifested in human RBCs lacking their expression [Wr(a−b−)].[6-8]

Over the years, interest in the Wr antigens has centered on their identity and on requirements for their surface presentation. Studies have focused on an interaction between glycophorin A (GPA) and band 3 (the anion exchanger), the two RBC transmembrane (TM) proteins in similar abundance.[9,10] Evidence for the involvement of GPA first came from the finding that GPA-deficient En(a−) RBCs do not display the Wr antigens.[6] Immunoprecipitation and reconstitution studies also indicated that the Wr^b antigen requires GPA and lipids for reactivity.[11,12] Proteolysis and chemical modification experiments suggested that amino acids 62 through 70 of GPA, a putative helical region,[11] engage the labile structure of the Wr^b antigen.[12] However, the independent segregation of Wr^a from GPA-borne M/N blood group antigens[13] and no apparent change in the residues 40 through 96 of GPA among Wr(a+b−), Wr(a+b+) and Wr(a−b+) individuals[12] suggested that the Wr antigens most likely involve an additional membrane component.

It was postulated that band 3 could be the candidate and its interaction with GPA might be responsible for the disposition of Wr antigens in the RBC membranes.[14] This view conciliated with the altered glycosylation of band 3 in En(a−) RBCs,[15] the decreased rotation of band 3 induced by anti-GPA antibodies,[16] and the aggregation of band 3 with GPA in the presence of Triton X-100 detergent.[12] Further support for the hypothesis came from more recent studies showing the coprecipitation of band 3 and GPA by anti-Wr^b antibodies[17,18] and the facilitation by GPA of band 3 expression in the Xenopus oocyte system.[19] Most recently, the Wr^a/Wr^b polymorphism was shown to result from an allelic change (A1972G) in the band 3 gene causing the Lys658Glu substitution.[20] This finding, together with the knowledge about natural variations of glycophorin,[21,22] suggests a model in which Glu_{658} of band 3 interacts with Arg_{61} of GPA to form the Wr^b antigen.[20] We examine here the model from a genetic evolutionary perspective and present data showing how structural changes in GPA and band 3 might reshape the protein-protein interaction and thus affect Wr^b antigen expression.

MATERIALS AND METHODS

Blood samples and serologic testing. Blood samples used as controls were obtained from normal human blood donors. Blood samples exhibiting variant phenotypes of the MNS blood group system were gifts from the following sources: M^kM^k, En(a−), and SAT bloods were from the Osaka Red Cross Blood Center (Osaka, Japan); MiV blood from the American Red Cross (Los Angeles, CA); Dantu and S-s-U- bloods were from the Community Blood Center (Dayton, OH); and St^a blood was from the Miyagi Red Cross Blood Center (Sendai, Japan). Blood samples of nonhuman primates were provided by the Wildlife Conservation Society (Bronx, NY), the Yerkes Primate Center (Atlanta, GA), or the Laboratory for Experimental Medicine or Surgery in Primates (Tuxedo, NY). The

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Wr^b antigen status on RBCs of animals was tested with human antiserum (MF) using standard hemagglutination techniques.

Isolation of DNA and RNA. Genomic DNAs were prepared from peripheral blood leukocytes as described.[24] Total RNA was isolated from hemolysates using a sequential cell lysis method[24] and then extracted with Trizol reagent (BRL, Gaithersburg, MD).

Synthesis and amplification of cDNA. Synthesis and amplification of cDNAs from erythroid total RNA was performed by reverse transcription-coupled polymerase chain reaction (RT-PCR), as previously described.[25] To obtain band 3 cDNA products, two primers that define, respectively, exons 16 and 17 of the human gene were used: AE1, 5′-AAACTCTCGGTGCCTGATGGCTTC-3′ (nt 1891-1914, sense), and AE2, 5′-GAGCCCTTGACCATCTTGCGCTCA-3′ (nt 2076-2099, antisense).[26-28]

To obtain GPA cDNAs from higher primates, the following human primers were used[25,29]: GP1, 5′-GTATGGAAAAATAATCTT-TGTATTAC-3′ (nt 3-28, exon 1 for signal peptide, sense); GP2, 5′-AGCATATCAGCAT(C/T)AAGTACCACT-3′ (nt 46-69, exon 2, sense); GP3, 5′-ATCACTTGTCTCTGGATTTTCTATTTC (nt 421-447, exon 6-7, antisense); and GP4, 5′-TCCACATTTGGTTTG-GTGAACAGATTC-3′ (nt 454-480, exon 7, antisense). GP3 and GP4 could only prime the synthesis of GPA cDNAs, because their sequences are located in the last two exons encoding the cytoplasmic domain and are not present in the GPB gene.[25,29] After first-strand synthesis, the GPA cDNA product was amplified 30 cycles in 50 μL volume on a thermocycler (Ericomp, San Diego, CA). The first 29 cycles were each run at 94°C for 1 minute, at 55°C for 45 seconds, and at 72°C for 1 minute. For the last cycle, annealing at 55°C and chain extension at 72°C was for 2 and 7 minutes, respectively.

Amplification of genomic DNA sequences. Exon 16 of the band 3 gene spanning the A1972G (Lys658Glu) polymorphism was amplified from total genomic DNA in the presence of two primers, AE1 (see above) and AE3 (5′-TCTCACGTGGTGATCTGAGACTCC-3′).[28]

DNA sequence determination. The PCR-amplified cDNA and genomic DNA products were purified by native 5% polyacrylamide gel electrophoresis and their nucleotide sequences were directly determined on an automated DNA sequencer (Applied Biosystem, Foster City, CA).

RESULTS

Band 3 and GPA expression in Wr(a−b−) and Wr(a−b+) individuals with MNSs-related variants. To further delineate the structure-phenotype relationship for the Wr^b antigen, the band 3 polymorphism and glycophorin expression were revisited in 7 individuals with MNSs-related variant phenotypes. These phenotypes included M^kM^k, En(a−), S-s-U-, St^a, MiV, Dantu, and SAT. Of the 7 individuals examined, all but the Dantu-positive proband were homozygotes. RBCs from these individuals were either deficient in glycophorins[23,30-32] or associated with expression of hybrid glycophorins resulting from unequal crossovers.[33-37] As determined by sequencing of PCR-amplified cDNA or genomic DNA products, all individuals carried the Glu_{658} but not the Lys_{658} form of band 3 (data not shown), indicating that they were all homozygotes for the Wr^b allele. In M^kM^k, En(a−), and S-s-U- cells, the Wr^b status apparently paralleled the absence or presence of GPA and correlated with the genetic status of the GPA gene. For RBCs bearing glycophorin hybrids except GPSat, the pattern of Wr^b antigen expression complied with the absence or presence of the GPA portion expressed (see below). These data showed that, without GPA, the Glu_{658} form of band 3 alone does not display the Wr^b determinant.

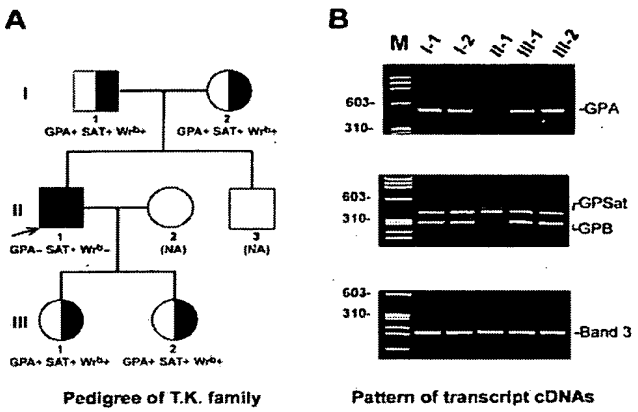

Fig 1. RT-PCR analysis of glycophorin and band 3 expression in the SAT(T.K.) family. (A) Pedigree of the family in which the status of GPA and SAT and Wr^b antigens is indicated. Note that propositus II-1 (indicated by arrow) was homozygous for the GPSat gene. NA, individuals not available for this study. (B) Pattern of transcript cDNAs for glycophorins and band 3 from the family members. The amplified cDNA products were separated on native 5% to 7% polyacrylamide gel electrophoresis and stained with ethidium bromide. The size of ϕX174 DNA *Hae* III markers (M) and the identity of cDNA species are indicated at the left and right margins, respectively. Note that neither GPA nor GPB product is seen in the SAT homozygote who lacked the Wr^b antigen on the RBC surface.

Expression and inheritance of the Wr^b antigen in SAT (T.K.) family. SAT is a private RBC antigen associated with the expression of two glycophorin isoforms in different families.[38] In the T.K. family, expression of the SAT antigen was accompanied by the inheritance of a GPA-B hybrid gene, GPSat, that arose via a similar mechanism as GPMiV but differed from the latter in the site of crossover point.[37] RT-PCR analysis of this three-generation family showed a genetic association but a phenotypic dissociation of band 3 with the Wr^b antigen. The erythroid cells from the five SAT-positive members all contained the band 3 and GPSat transcripts; nevertheless, in contrast to the heterozygotes, the homozygote (donor II-1) lacked both GPA and GPB transcripts (Fig 1). Although sequencing of the band 3 cDNAs showed that all individuals should be the Glu_{658} homozygotes, the Wr^b antigen was segregated from GPSat in donor II-1 but was cotransmitted with GPA in members of the first and third generations (Fig 1). This inheritance pattern reinforced the hypothesis that the Wr^b antigen requires a specific interaction between the band 3 and GPA proteins.[14,17,20]

Conformational dependence of the Wr^b antigen and role of GPA TM junction. It has been suggested that the region of GPA, from residues 62 through 70, involves the Wr^b antigen and forms part of an α-helix immediately adjacent to the TM segment.[11,12] Definition of the sequence as part of theWr^b epitope is supported by the absence of the Wr^b anti-

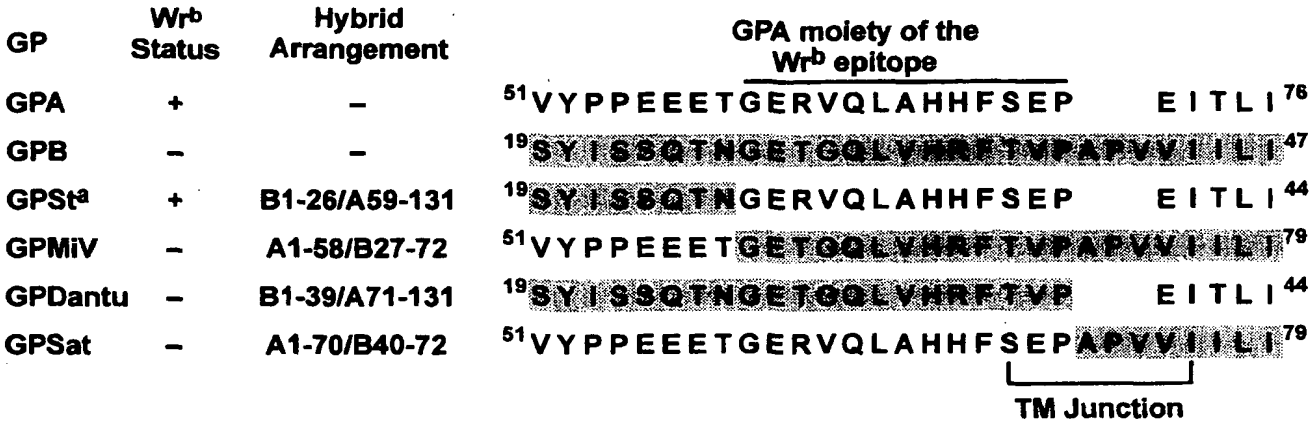

Fig 2. Comparison of the amino acid sequences between the parent and hybrid glycophorins in the region relevant to Wr^b antigen exhibition. GPA and GPB, the parent molecules, are shown above GPSt^a, MiV, Dantu, and Sat, the hybrid molecules. The GPA sequence that may engage the labile structure of theWr^b antigen is overlined. GPB and the GPB-derived sequences are shaded. The arrangement of hybrids with respect to the GPA and GPB polypeptides and their status associated with Wr^b are shown. Note that GPSt^a versus GPMiV and GPDantu versus GPSat are two pairs of reciprocal protein products whose crossing-over points in the genes reside in introns 3 and 4, respectively. The TM junction that interfaces the extracellular and membrane-spanning domains of glycophorins is indicated.

gen in MiV RBCs that express a GPA-B hybrid lacking GPA residues 59 through 71[35,36] (Fig 2).

However, the occurrence of linear sequences involving the interaction may not always lead to Wr^b antigen expression. As shown, the SAT homozygous RBCs expressed the Glu_{658} form of band 3 and the hybrid glycophorin, GPSat (Fig 1). Comparison of the amino acid sequences (Fig 2) shows that the hybrid structure of GPSat is reciprocal to that of GPDantu[39,40] and distal to that of GPMiV[35,36] or GPSt^a.[41] Thus, GPSat retains the entire extramembrane domain of GPA from residues 1 through 71, including the moiety for the Wr^b epitope, and differs from GPA in the extramembranous junction and TM segment (Fig 2). The lost Wr^b expression in the SAT homozygote strongly suggests that formation of the epitope depends on proper contact of the two proteins and that the TM junction of GPA plays an important role in maintaining the required conformation. This notion is consistent with our recent studies showing the conformational dependence of the S, s and U antigens and the importance of the GPB TM junction for their presentation.[42] In the case of GPSat, it is likely that the insertion of three GPB residues (Ala-Pro-Val) at the TM junction could readjust the orientation of the preceding α-helix and thus alter the native antigen structure necessary for anti-Wr^b binding. This is different from GPSt^a or GPMiV, in which the retention or loss of the Wr^b epitope sequence (Fig 2) has caused a coprecipitation and a null reaction with the anti-Wr^b antibody, respectively.[11,43]

Sequence polymorphisms of GPA and band 3 protein homologues in nonhuman primates. Among nonhuman primates, only chimpanzee RBCs express the Wr^b antigen at a level comparable to humans, whereas RBCs from orangutans, gibbons, and rhesus monkeys essentially lack the serologic reaction.[44,45] Because thedefinition of such positive or negative status could show the underlying structural diversity, we determined the Wr^b antigen status on animal RBCs and sequenced their cDNAs encoding the homologues of GPA and band 3 proteins. Comparison of the deduced primary sequences encompassing the Wr^b domain (Fig 3) showed that (1) the GPA homologues are more divergent

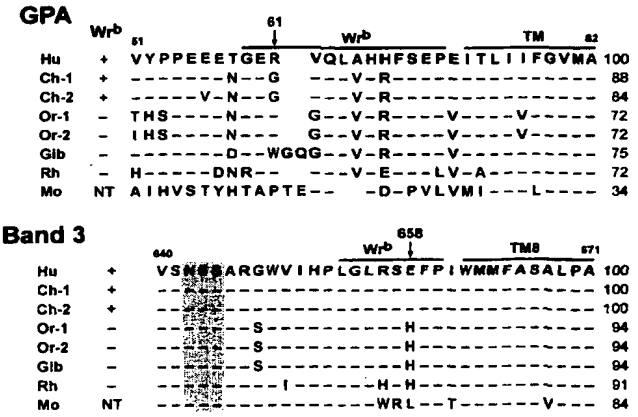

Fig 3. Deduced amino acid sequences of GPA and band 3 protein homologues from nonhuman primates. (Top) GPA sequences. For clarity, only those amino acid residues corresponding to positions 51 through 82 of human GPA are shown. Amino acid differences are spelled out and identical residues are denoted by dashes. (Bottom) Band 3 sequences. Sequences corresponding to residues 640 through 671 of human band 3 are aligned. The N-glycosylation consensus sequence NSS is shaded. Designation of species: Hu, human; Ch, chimpanzee; Or, orangutan; Gib, gibbon; Rh, rhesus; and Mo, mouse. Ch-1, Ch-2, and so on denote unrelated individuals. The deduced sequences of the two proteins were obtained from the same animals, except those for mouse glycophorin[46] and mouse band 3.[47] Arg_{61} of GPA and Glu_{658} of band 3 are indicated by vertical arrows. The sequences tentatively assigned as the interacting domain for Wr^b are overlined and so are the portions of the TM segment of the two proteins. The Wr^b antigen status on RBCs of each animal is shown at left: +, positive; –, negative; and NT, not tested. The percentage of identity of the animal sequence relative to the human sequence (100%) is indicated at the right margin.

than the band 3 homologues in different species, but the former have a number of conserved amino acids in positions 62 through 71, including $Gln_{63}Leu_{64}$, His_{66}, and $Phe_{68}Ser_{69}$-Glu_{70}; and (2) both Arg_{61} of GPA and Glu_{658} of band 3, the two residues thought to be critical in forming the Wr^b antigen,[20] are variable from rhesus to chimpanzee.

As shown for GPA sequences (Fig 3, top), Arg_{61} was present in the orangutan and rhesus but was replaced by Gly and Trp in the chimpanzee and gibbon. Scattered changes in positions 51 through 82 included unique insertion or random mutations, but positions 65 and 67 were occupied by reiterated substitutions in different species. Accordingly, Val65Ala and Arg67His distinguish chimpanzee from human. In orangutan or gibbon, one more change, Val → Gly_{62}, made the GPA sequence in positions 62 through 67 be identical with the human GPB sequence in positions 30 through 35 (Gly-Gln-Leu-Val-His-Arg; Figs 2 and 3). In the rhesus, its GPA differed from human GPA by three residues in positions 62 through 71 (Val65Ala, Glu67His, and Leu71Pro; Fig 3). In mice, a low sequence identity (34%) is mainly confined to the TM segment and there is no significant homology in the Wr^b domain.[46]

Regarding the band 3 sequence (Fig 3, bottom), the region encompassing the extracellular loop and the adjacent membrane-spanning segment (TM 8th pass) is well conserved and, even in mice,[47] the sequence identity is as high as 84%. In that region, the chimpanzee had an identical sequence with humans. The orangutan/gibbon and rhesus/baboon pairs each shared the same sequence, with two or three substitutions located between the N-glycosylation site and TM 8 (data for baboon not shown). Of all animals examined, no Lys_{658} form of band 3 was detected, suggesting that the Wr^a antigen may also be rare in nonhuman primates. Nevertheless, Glu_{658} occurred in chimpanzees, but it had been replaced by a histidine residue in other species.

Correlation of sequence variation with Wr^b antigen expression in nonhuman primates. It is evident that the proposed Arg_{61}-Glu_{658} charge pair[20] cannot be formed in the animals studied due to the substitution of either one or both residues (Fig 3). This finding suggests that Arg_{61} of GPA is dispensable or replaceable with respect to the Wr^b reactivity, at least in the case of chimpanzees. Comparable Wr^b expression in human and chimpanzee RBCs (Fig 3) also implied that the two other changes in the helical region, Ala → Val_{65} and His → Arg_{67}, may not affect the overall structure of the antigen. In the orangutan and gibbon, the absent Wr^b expression was apparently correlated with changes of Glu → His_{658} on band 3 and Val → Gly_{62} on GPA, because the former removed a negative charge and the latter rendered the sequence more like GPB, which is known not to display the Wr^b reactivity (Fig 2). Similarly, the lack of Wr^b expression on rhesus RBCs could also be attributed to changes on both band 3 (Glu→His_{658}) and GPA. Regarding the rhesus GPA moiety, the Arg67Glu change introduced a negative charge, and the substitution by Leu of conserved Pro_{71}, a helix breaker, might perturb the local conformation and thus alter the interaction. It is notable that, $Ser_{69}Glu_{70}$ in the TM junction of GPA may also be important for the GPA-band 3 interaction, because they differ from human GPB (Fig 2) but are conserved from the rhesus to humans (Fig 3, top).

DISCUSSION

In contrast to the Wr^a antigen that may be formed by band 3 alone, there is considerable evidence indicating the dependence of Wr^b antigenicity on a specific GPA-band 3 interaction.[12-19] Nevertheless, the nature of this protein-protein interaction as well as the role of individual amino acid residues in Wr^b antigen formation remains largely speculative. The difficulty in defining this interaction stems partly from the fact that single amino acid changes in the regions encompassing GPA residues 62 through 70 and band 3 residues 651 through 660 are seldom encountered in the human populations, despite the recent finding of a rare Lys_{658} polymorphism on the band 3 protein.[20] This report describes two novel observations concerning the expression of the Wr^b antigen. The first observation is that the alteration of TM junction in GPSat silences the human antigen. The second observation points to a correlation of the Wr^b status with sequence variations on GPA and band 3 homologues in nonhuman primates. These data provide new insights, in the context of primary structures, into the molecular basis for the GPA-band 3 interaction and its relationship with Wr^b exhibition.

Of the Wr^b null phenotypes found in human RBCs, the one associated with SAT homozygous cells is particularly intriguing in that GPSat retains an apparently intact sequence essential for the antigen presentation. The antigen disruption in GPSat by a small insertion distal to the putative Wr^b domain raises the possibility that the extramembranous junction or adjacent TM residues participate in or influence the GPA-band 3 interaction. Although both contain the Wr^b moiety, GPSat makes a contrast with $GPSt^a$, because the latter expressed the antigen weakly[11] and carried a GPB sequence[41] proximal to the residues 62 through 70. This comparison indicates that the Wr^b antigen is sensitive to local structural changes and that the closer the alteration is to the TM segment, the more profound the conformational perturbation.

The definition of Wr^b positivity or negativity in nonhuman primates by inspection of sequence divergence and conservation broadens our view on the human counterpart from an evolutionary perspective. Our data suggest that Glu_{658} of band 3 and VQL_{62-64}, His_{66}, and $FSEP_{69-71}$ of GPA are important for the GPA-band 3 interaction and Wr^b antigen exhibition, whereas Arg_{61}, Ala_{65}, and His_{67} are not so crucial. Although scattered amino acid variations proximal to position 58 of GPA occur in animals (Fig 3), they are unlikely to be crucial either, because $GPSt^a$ carries a completely different sequence proximal to that position (Fig 2), yet still displays the Wr^b reactivity.[11] Apparently, the role of the GPA moiety for epitope formation mainly involves amino acids that are located in the helical region and TM junction. In addition, the associated Wr^b expression in the absence of Arg_{61}, but presence of Arg_{67}, in chimpanzee GPA suggests that the overall surface charge of the α-helix, rather than the specific location of Arg residues, would be more important, if the ionic interaction with Glu_{658} of band 3 occurs at all.

Because parallel packing of the TM α-helices of the two proteins would bring the preceding extramembranous portions in close proximity, the helical region of GPA may stabilize the interaction and therefore the Wr^b antigen by forming additional contacts with the residues nearby Glu_{658} of the band 3 protein.

In summary, the present studies have provided evidence for the conformational dependence of the Wr^b antigen and led to the identification of certain amino acid residues that may be important for its exhibition. Nevertheless, although the Wr^b antigen may be considered a phenotypic indicator of the GPA-band 3 interaction, its lost expression does not necessarily mean the abolition of the interaction. How those local changes cause the phenotypic silencing of Wr^b and whether they reshape the interaction to elicit new antigenicities, such as SAT and St^a, are some of the issues that remain to be investigated. Studies combining site-directed mutagenesis with cotransfection of GPA and band 3 cDNAs in an ex vivo system should allow one to dissect in depth the structural elements involved in such protein-protein interactions.

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REFERENCES

1. Holman CA: A new rare human blood-group antigen (Wr^a). Lancet 2:119, 1953

2. Telen MJ: Erythrocyte blood group antigens: Not so simple at all. Blood 85:299, 1995

3. Adams J, Broviac M, Brooks W, Johnson NR, Issitt PD: An antibody, in the serum of a Wr(a+) individual, reacting with an antigen of high frequency. Transfusion 11:290, 1971

4. Wren MR, Issitt PD: Evidence that Wr^a and Wr^b are antithetical. Transfusion 28:113, 1988

5. Mollison PI, Engelfreit CP, Contreras M: Blood Transfusion in Clinical Medicine. Oxford, UK, Blackwell Scientific, 1993, p 276

6. Issitt PD, Pavone BG, Wagstaff W, Goldfinger D: The phenotypes En(a−), Wr(a−b−) and En(a+) Wr(a+b−), and further studies on the Wr and En blood group systems. Transfusion 16:396, 1976

7. Togunaka E, Sasakava S, Tamaka K, Kawamata H, Giles CM, Ikin EW, Poole J, Anstee DJ, Mawby WJ, Tanner MJA: Two apparently healthy Japanese individuals of type M^kM^k have erythrocytes which lack both the blood group MN and Ss-active sialoglycoproteins. J Immunogenet 6:383, 1979

8. Vengelen-Tyler V, Anstee DJ, Issitt PD, Pavone BG, Ferguson SJ, Mawby WJ, Tanner MJA, Blajchman MA, Lorque P: Studies on the blood of an Mi^V homozygote. Transfusion 21:1, 1981

9. Steck TL: The organization of the proteins in the human red cell membrane. J Cell Biol 62:1, 1974

10. Blumenfeld OO, Adamany AM: Structural polymorphism within the amino-terminal region of MM, NN, and MN glycoproteins (glycophorins) of the human erythrocyte membrane. Proc Natl Acad Sci USA 75:2727, 1978

11. Ridgwell K, Tanner MJA, Anstee DJ: The Wr^b antigen, a receptor for Plasmodium falciparum malaria, is located on a helical region of the major membrane sialoglycoprotein of the human red blood cells. Biochem J 209:273, 1983

12. Dahr W, Wilkinson S, Issitt PD, Beyreuther K, Hummel M, Morel P: High frequency antigens of the human erythrocyte membrane sialoglycoproteins, III. Studies on the En^aFR, Wr^b and Wr^a antigens. Biol Chem Hoppe Seyler 367:1033, 1986

13. Pavone BG, Issitt PD, Wagstaff W: Independence of Wright from many other blood group systems. Transfusion 17:47, 1977

14. Dahr W: Immunochemistry of sialoglycoproteins in human red blood cell membrames, in Vengelen-Tyler V, Judd WJ (eds): Recent Advances in Blood Group Biochemistry. Arlington, VA, American Association of Blood Banks, 1986, p 23

15. Gahmberg CG, Myllyla G, Leikola J, Pirkola A, Nordling S: Absence of the major sialoglycoprotein in the membrane of human En(a−) erythrocytes and increased glycosylation of band 3. J Biol Chem 251:6108, 1976

16. Nigg EA, Bron EA, Girardel M, Cheryl RJ: Band 3-glycophorin A association in erythrocyte membranes demonstrated by combining protein diffusion measurements with antibody-induced cross-linking. Biochemistry 19:1887, 1980

17. Telen MJ, Chasis JA: Relationship of the human erythrocyte Wr^b antigen to an interaction between glycophorin A and band 3. Blood 76:842, 1990

18. Ring SM, Tippett P, Swallow DA: Comparative immunochemical analysis of the Wr^a and Wr^b red cell antigens. Vox Sang 67:226, 1994

19. Groves JD, Tanner MJA: Glycophorin A facilitates the expression of human band 3-mediated anion transport in Xenopus oocytes. J Biol Chem 267:22163, 1992

20. Bruce LJ, Ring SM, Anstee DJ, Reid ME, Wilkinson S, Tanner MJA: Changes in the blood group Wright antigens are associated with a mutation at amino acid 658 in human erythrocyte band 3:A site of interaction between band 3 and glycophorin A under certain conditions. Blood 85:541, 1995

21. Huang C-H, Johe KK, Seifter S, Blumenfeld OO: Biochemistry and molecular biology of MNSs blood group antigens. Clin Haematol 4:821, 1991

22. Cartron JP, Rahuel C: Human erythrocyte glycophorins: Protein and gene structure analyses. Transfus Med Rev 6:63, 1992

23. Huang C-H, Johe KK, Moulds JJ, Siebert PD, Fukuda M, Blumenfeld OO: δ Glycophorin (glycophorin B) gene deletion in two individuals homozygous for the S-s-U- blood group phenotype. Blood 70:1830, 1987

24. Goossens M, Kan YW: DNA analysis in the diagnosis of hemoglobin disorders. Methods Enzymol 76:805, 1981

25. Huang C-H, Reid ME, Blumenfeld OO: Exon skipping caused by DNA recombination that introduces a defective donor splice site into the human glycophorin A gene. J Biol Chem 268:4945, 1993

26. Tanner MJA, Martin PG, High S: The complete amino acid sequence of the human erythrocyte anion transporter protein deduced from the cDNA sequence. Biochem J 256:703, 1988

27. Lux SE, John KM, Kopito RR, Lodish HF: Cloning and characterization of band 3, the human erythrocyte anion exchange protein. Proc Natl Acad Sci USA 86:9089, 1989

28. Schofield AE, Martin PG, Spillett D, Tanner MJA: The structure of the human red cell anion exchanger (EPB3, AE1, band 3) gene. Blood 84:2000, 1994

29. Huang C-H, Xie SS, Socha W, Blumenfeld OO: Sequence diversification and exon inactivation in the glycophorin A gene family from chimpanzee to human. J Mol Evol 41:478, 1995

30. Tate CG, Tanner MJA, Judson PA, Anstee DJ: Studies on human red cells glycophorin A and glycophorin B genes in glycophorin-deficient individuals. Biochem J 263:993, 1989

31. Vignal A, London J, Rahuel C, Cartron JP: Promoter sequence

and chromosomal organization of the genes encoding glycophorin A, B, and E. Gene 95:289, 1990

32. Rahuel C, London J, Vignal A, Cherif-Zahar B, Collin Y, Siebert, Fukuda M, Cartron JP: Alteration of the genes for glycophorin A and B in glycophorin A-deficient individuals. Eur J Biochem 177:605, 1988

33. Rearden A, Phan H, Dubnicoff T, Kudo S, Fukuda M: Identification of the crossing-over point of a hybrid gene encoding human glycophorin variant St^a. J Biol Chem 265:9259, 1990

34. Huang C-H, Blumenfeld OO: Characterization of a genomic hybrid specifying the human erythrocyte antigen Dantu: Dantu gene is duplicated and linked to a δ glycophorin gene deletion. Proc Natl Acad Sci USA 85:9640, 1988

35. Huang C-H, Blumenfeld OO: Identification of recombination events resulting in three hybrid genes encoding human MiV, MiV(J.L.) and St^a glycophorins. Blood 77:1813, 1991

36. Vignal A, Rahuel C, El maliki B, London J, Le Van Kim C, Blanchard D, Andre C, d'Auriol L, Galibert F, Blajchman MA, Cartron JP: Molecular analysis of glycophorin A and B gene structure and expression in homozygous Miltenberger class V (MiV) human erythrocytes. Eur J Biochem 184:337, 1989

37. Huang C-H, Reid ME, Okubo Y, Daniels GL, Blumenfeld OO: Glycophorin SAT of the human erythrocyte membrane is specified by a hybrid gene reciprocal to glycophorin Dantu gene. Blood 85:2222, 1995

38. Daniels GL, Green CA, Okubo Y, Seno T, Yamaguchi H, Ota S, Taguchi T, Tomonari Y: SAT, a 'new' low frequency blood group antigen, which may be associated with two different MNS variants. Tranfus Med 1:39, 1991

39. Blumenfeld OO, Smith AJ, Moulds JJ: Membrane glycophorins of Dantu blood group erythrocytes. J Biol Chem 262:11864, 1987

40. Dahr W, Beyreuther K, Moulds J, Unger P: Hybrid glycophorins from human erythrocyte membranes. I. Isolation and complete structural analysis of the hybrid sialoglycoprotein from Dantu-positive red cells of the N.E. variety. Eur J Biochem 166:31, 1987

41. Blanchard D, Dahr W, Beyreuther K, Moulds J, Cartron JP: Hybrid glycophorins from human erythrocyte membranes. Isolation and complete structural analysis of the novel sialoglycoprotein from St(a+) red cells. Eur J Biochem 167:361, 1987

42. Huang C-H, Reid ME, Blumenfeld OO: Remodeling of the transmembrane segment in human glycophorin by aberrant RNA splicing. J Biol Chem 269:10804, 1994

43. Chasis JA, Reid ME, Jensen RH, Mohandas N: Signal transduction by glycophorin A: Role of extracellular and cytoplasmic domains in a modulatable process. J Cell Biol 107:1351, 1988

44. Nichols M: Monoclonal antibodies with red cell specificities, in Moulds JM, Masouredis SP (eds): Monoclonal Antibodies. Arlington, VA, American Association of Blood Banks, 1989, p 27

45. Rearden A: Heterogeneity in the specificity of Wr^b monoclonal antibodies, in Rouger P, Salmon C (eds): Monoclonal Antibodies Against Human Red Blood Cell and Related Antigens. Paris, France, 1987, p 261

46. Matsui Y, Natori S, Obinata M: Isolation of the cDNA clone for mouse glycophorin, erythroid-specific membrane protein. Gene 77:325, 1989

47. Kopito RR, Lodish HF: Primary structure and transmembrane orientation of the murine anion exchange protein. Nature 316:234, 1985